

## **Advanced Methods for Passive Acoustic Detection, Classification, and Localization of Marine Mammals**

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### **LONG-TERM GOALS**

For effective long-term passive acoustic monitoring of today's large data sets, automated algorithms must provide the ability to detect and classify marine mammal vocalizations and ultimately, in some

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cases, provide data for estimating the population density of the species present. In recent years, researchers have developed a number of algorithms for detecting calls and classifying them to species or species group (such as beaked whales). Algorithms must be robust in real ocean environments where non-Gaussian and non-stationary noise sources, especially vocalizations from similar species, pose significant challenges. In this project, we are developing improved methods for detection, classification, and localization of many types of marine mammal sounds.

## OBJECTIVES

We are developing advanced real-time passive acoustic marine mammal detection, classification, and localization methods using a two-pronged approach: developing improved DCL algorithms, and developing standardized interfaces and software.

First, we are developing, testing, and characterizing advanced DCL algorithms:

1. Echolocation click classification. Algorithms are being developed and tested for several species of beaked whales and small odontocetes.
2. Tonal signal detection and classification. Algorithms are being tested for several species of mysticetes and for small odontocetes.
3. Multi-sensor localization. Algorithms will be developed and tested on datasets containing sounds of both odontocetes and mysticetes.

Second, improved DCL software will be developed and both existing and new methods will be made available to users. The key contribution will be the development of four well-specified interfaces, for detection, feature extraction, classification, and localization. We will implement the “front end” of these interfaces in widely-used and critical software packages, Ishmael and M3R, to supply acoustic data and metadata across the interfaces. Our “back end” implementations will encode DCL algorithms that can be plugged into any of the front ends to analyze acoustic data supplied across the interfaces. The aim is to make it simple for users to take advantage of these algorithms, and for developers to implement new methods in a simple, straightforward way and thus make them available to end users. We will conduct performance assessments of the improved algorithms and software interfaces using annotated data sets in the laboratory, and perform a demonstration using real time data at a US Navy instrumented range.

## APPROACH

**Odontocete click detection and classification.** A multiclass support vector machine (SVM) classifier was previously developed (Jarvis et al. 2008). This classifier both detects and classifies echolocation clicks from five species of odontocetes, including Blainville’s and Cuvier’s beaked whales, Risso’s dolphins, short-finned pilot whales, and sperm whales. Here Moretti’s group, especially S. Jarvis, will improve the SVM classifier by resolving confusion between species whose clicks overlap in frequency. The proposed work will investigate alternate feature sets to better separate species in the SVM’s decision space.

Roch et. al’s current real-time system for odontocete click classification is based upon Gaussian mixture models using cepstral feature vectors. Cepstral feature vectors provide a compact

representation of the spectrum (Rabiner and Juang 1993) that let the system represent echolocation spectra using a reduced number of coefficients, providing a lower-dimensional feature space than using a standard representation of the spectrum. This system will be extended to cover more species and more recording/noise environments. In a separate project, Roch is working with personnel at Univ. Calif. San Diego on developing new features based on subspace models and improved noise compensation. The subspace models use hierarchical principal components analysis and random-projection trees (Freund et al. 2007) to learn new feature sets that will be used in place of cepstral feature vectors. The noise modeling will examine how to more effectively estimate background noise and compensate for it, taking into account interactions between noise and source (Ross 1976).

**Tonal signal detection and classification.** “Tonal signal” is a generic term for frequency-modulated calls such as baleen moans or odontocete whistles. Methods for detecting and classifying such sounds will be developed and applied to both odontocete whistles and to vocalizations from blue (*Balaenoptera musculus*), minke (*B. acutorostrata*), and humpback (*Megaptera novaeangliae*) whales. The methods to be developed here determine the species associated with odontocete whistles that are extracted automatically via the *Silbido* tonal contour following system (Roch et al. 2010). Research led by Roch focuses on the areas of signal processing and *Silbido*’s search algorithm to further refine this algorithm. Echolocation clicks result in broad-band energy producing interfering peaks in the time-frequency domain. These will be mitigated by locating echolocation clicks through an existing detection algorithm (Soldevilla et al. 2008, Roch et al. 2011) based on Teager energy (Kaiser 1990, Kandia and Stylianou 2006), and then removing it by interpolation.

In observing expert analysts classify whistles to species, we have noted that experts tend to comment on the general shape of a whistle. Extracted contours will be classified to species using hidden Markov models which are capable of modeling temporal transitions, thus exploiting the shape. HMMs have been used previously to classify signature whistles to groups, but a general approach requires more general models that can capture inter-specific variation. We propose segmenting whistles into components based upon easily identifiable landmarks (e.g. inflection points), and creating multiple models for components based upon cluster analysis.

Another approach will be to develop improved feature extraction methods that are based on processing units in the mammalian visual and auditory systems. It has been known for nearly 50 years that neurons in the visual cortex are sensitive to lines and surface edges in the visual field (Hubel and Wiesel 1962, Landy and Movshon 1991), and for at least 25 years that the auditory system has similar units for detecting frequency changes in tonal signals at specific frequencies (Mendelson and Cynader 1985). Mellinger and Martin will lead the effort to test some feature extraction and classification methods that use similar types of processing – specifically, developing processing units that respond to frequency change of a tonal signal within a narrow frequency range at specified FM rates, then modeling the time evolution of these units using a hidden Markov model (HMM) as described above.

**Advanced localization algorithms.** The first requirement for passive acoustic localization of marine mammals is the need to associate the detection of an individual signal as it is received across the array of widely spaced hydrophones. Moretti will lead the effort to develop a “nearest neighbor” approach to detection association. This approach will still use TDOA/hyperbolic methods, but will not discard TDOA from pairs of detections when the normally requisite 3 detections are not achieved. Rather, detections from a given hydrophone will be associated with detections from all of its nearest neighbors and pair-wise TDOAs will be calculated.

Mellinger will also lead an effort to investigate an advanced localization method that employs the full cross-correlation function. The standard TDOA method extracts the position of the peak of the cross-correlation function between two hydrophones, and effectively ignores the rest of the cross-correlation. If the wrong peak is picked – which can happen easily due to multipath effects or, less commonly, interfering sounds – there is no information present to indicate that any other choice may have been nearly as good. Here we propose to use a system that uses the entire cross-correlation function for each hydrophone pair in finding the optimum location.

**Software and interfaces.** An Application Programming Interface (API) is a specification of a set of procedure calls (for objects, methods), data types (scalars, structures, classes, etc.), and protocols for use of the procedures and data types. A properly constructed and documented API makes it relatively simple for a developer to add new algorithms to an existing system. Systems with well-designed APIs permit users to add new functionality in a straightforward manner. Ishmael's (Mellinger 2001) interfaces for detection and localization comprise a relatively complex set of object class methods (procedure calls) and data types; although it is standardized, it is hardly straightforward or well-documented. The M3R system (Morrissey et al. 2006) has a format for standardized data serving and detection message passing using multicast over dedicated private networks. M3R also has a message-passing facility to share detection and classification results (i.e., notification of detection/classification events). Martin, Moretti, and Mellinger will lead the effort to develop and test APIs to make it relatively simple for developers to code new algorithms and test them in the Ishmael and M3R systems.

## **WORK COMPLETED**

*Meetings, data sharing site, and funding:*

- (1) We have had monthly project teleconference meetings to discuss both technical details and project logistics. We also had a face-to-face meeting during the Acoustical Society conference in San Diego at the beginning of November 2011.
- (2) We established a private Internet-accessible site for data sharing and have placed twelve data sets in it for use by project participants. This site is accessed at <ftp.pmel.noaa.gov> with username ADCL; contact the authors for required further login information. The site is private because some of the data, while not classified, is considered sensitive.
- (3) Funding for the first year of the project reached all project members. Year-2 funding has been slow to reach project members, particularly OSU and SDSU, because of delays in transferring funds from NOAA to OSU; essentially, the funds didn't reach NOAA until just days after NOAA's annual transfer date, meaning that a special transfer was needed. This cannot happen until the new federal fiscal year; we are currently planning to do it in October 2012.

*Detection/Classification Algorithms:*

For baleen whale species utilizing tonal detection methods: Tonal (frequency contour) detection for mysticete species sounds under ~2 kHz has shown good results in the case of minke whale boing sounds (Mellinger et al. 2011). Effort is underway to extend the tonal detector to include additional candidate features: signal level; the Dominant Spectral Component (DSC), a form of peak frequency; and a measure of the sweep rate.

The DSC has now been published (Martin et al. 2012). The term DSC is utilized vice peak frequency due to potential variations in peak frequency that exist depending upon the bandwidth of the acoustic recording system and distance of the acoustic sensor from the animal. How observed peak frequency is different due to recording system bandwidth capability is obvious; however, the potential variation in peak frequency with distance is less obvious. Bottom-mounted hydrophones at naval ranges (e.g., the Pacific Missile Range Facility, PMRF) are typically at least a few kilometers distant from the animals due to the water depth in the area. The complex minke boing sounds, with energy extending over 10 kHz, can be detected from animals 50 km from a hydrophone. However, at these distances the nominal 1400 Hz component of the signal is the only component typically detected due to absorption of sound with distance, and hence termed the dominant component. The same sound detected at close range may have a very different peak frequency (e.g., 4 kHz). This same process of peak frequency variation as a function of distance also applies to echolocation clicks such as beaked whale foraging clicks due to the differential absorption of sound by seawater over a large frequency span. The DSC has also been observed with low standard deviation for a single individual minke whale at PMRF over several hours (1383 Hz  $\pm$  1.8 Hz s.d.) and is useful in automatically associating the same sound on multiple widely spaced sensors, a process useful for localization.

Another new method for extracting features from frequency sweeps is under development. Termed “kernel-group spectrogram correlation,” it uses a family of kernels operating on a normalized spectrogram to find time-frequency locations at which tonal sounds, such as delphinid whistles or baleen whale tonal calls, are changing frequency ( $df/dt$ ) at or near a specified rate.

Another component of our work on whistle classification has concentrated on increasing the purity of the automatically generated whistle clusters prior to training hidden Markov models.

A new method for employing support vector machines (SVM) to multi-class classification problems has also been developed. The new method is called the class-specific support vector machine (CS-SVM). A CS-SVM has been developed to classify click vocalizations from six species of odontocetes: Blainville’s beaked whales (foraging clicks), Cuvier’s beaked whales (foraging clicks), short-finned pilot whales, Risso’s dolphins, sperm whales and pantropical spotted dolphins.

#### *Localization Algorithms:*

Time-difference-of-arrival (TDOA) estimation is typically done by cross-correlation. We developed a method for cross-correlation that uses clicks synthesized from times and amplitudes of peaks in the input signal.

Another localization method being developed uses intersecting hyperbolae from successive clicks in an echolocation sequence. Traditional multilateration requires the detection of a given signal by at least 3 widely separated sensors. Many odontocetes, including beaked whales, are known to emit vocalizations that are highly directive. While the source level of these vocalizations is estimated to be in excess of 200 dB re: kPa, the narrow beam width means that often only single sensors or pairs of sensors are ensonified at a time. Yet the animals are also known to sweep their heads as they forage for food and emit echolocation clicks. This head sweep over time allows for different nearby pairs of sensors to detect individual clicks. The TDOA between pairs of hydrophones defines a hyperbola in two dimensions (X-Y, with depth assumed constant). An algorithm was developed to plot the intersection of the hyperbolae from disparate pairs of hydrophones that receive different echolocation clicks in a sequence.

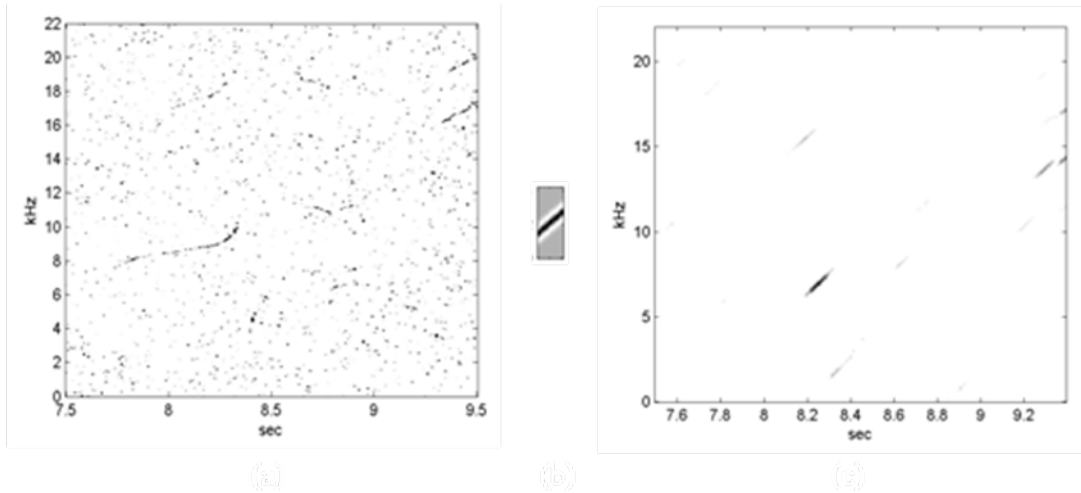
### Software:

The architecture for writing detection, classification, and localization modules has been completed and communication between Ishmael and a test module has been established. The architecture provides a translation library for each DCL platform supported that marshals data into a format that can be shared with other processes. Modules run as separate programs that share a limited region of memory with the DCL platform. This allows modules written on platforms that require separate processes (e.g. MATLAB, R) to be gracefully handled. User's designing classification modules will configure the DCL platform to send data to their module and make calls to a standard interface library. Results are sent back to the DCL platform in a similar manner.

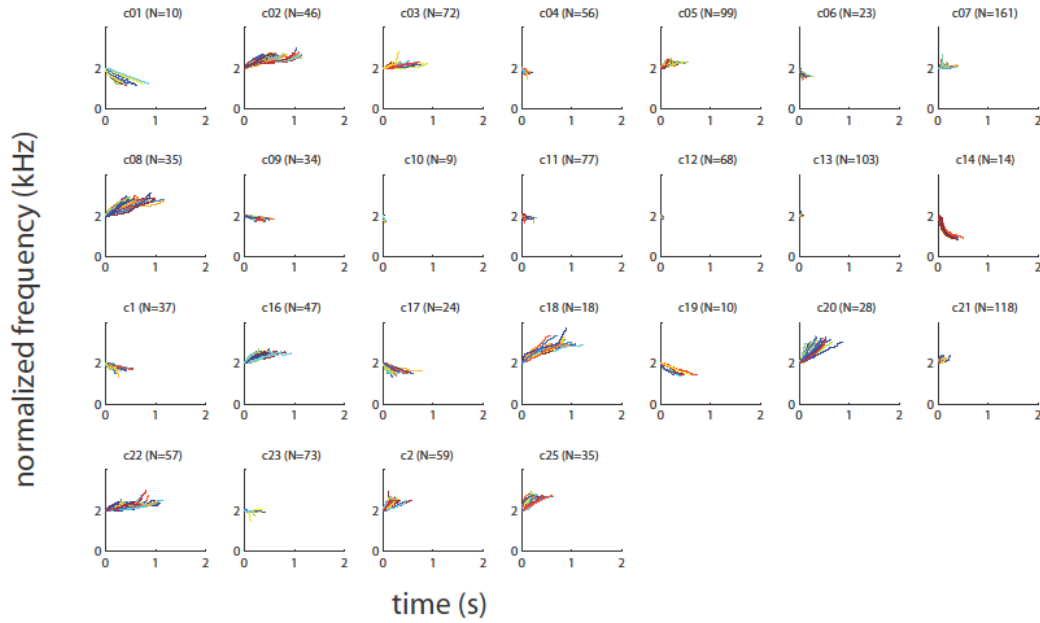
## RESULTS

*Kernel-group spectrogram correlation approach:* For each member of the kernel family, the result is a feature map representing the likelihood that a tonal call with the specified sweep rate is present. Figure 1 shows an example of this. Linking together successive feature maps allows accurate tracking of the tonal vocalization and extraction of further features.

*Clustering approach:* An example of the clustering results can be seen for spinner dolphin whistles (Fig. 2).

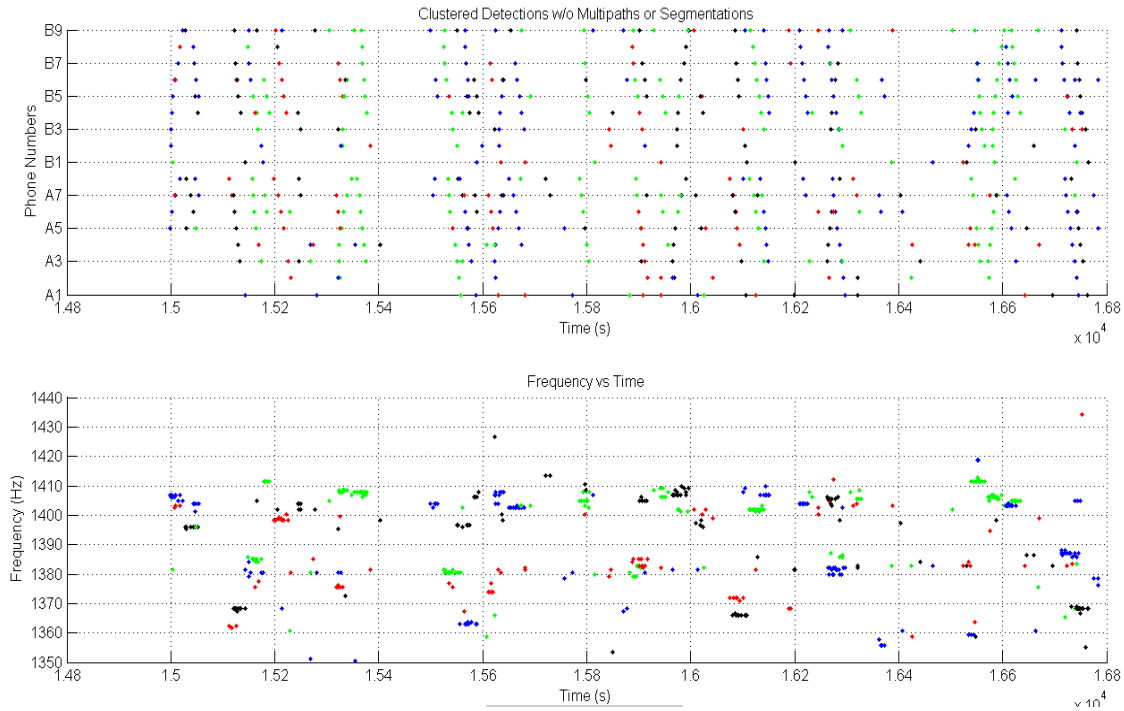


**Figure 1. A single instance of feature extraction by kernel-group spectrogram correlation. (a) Normalized spectrogram. (b) Correlation kernel, showing positive (dark) and negative (light) regions. (c) Feature map resulting from cross-correlation of (a) and (b).**



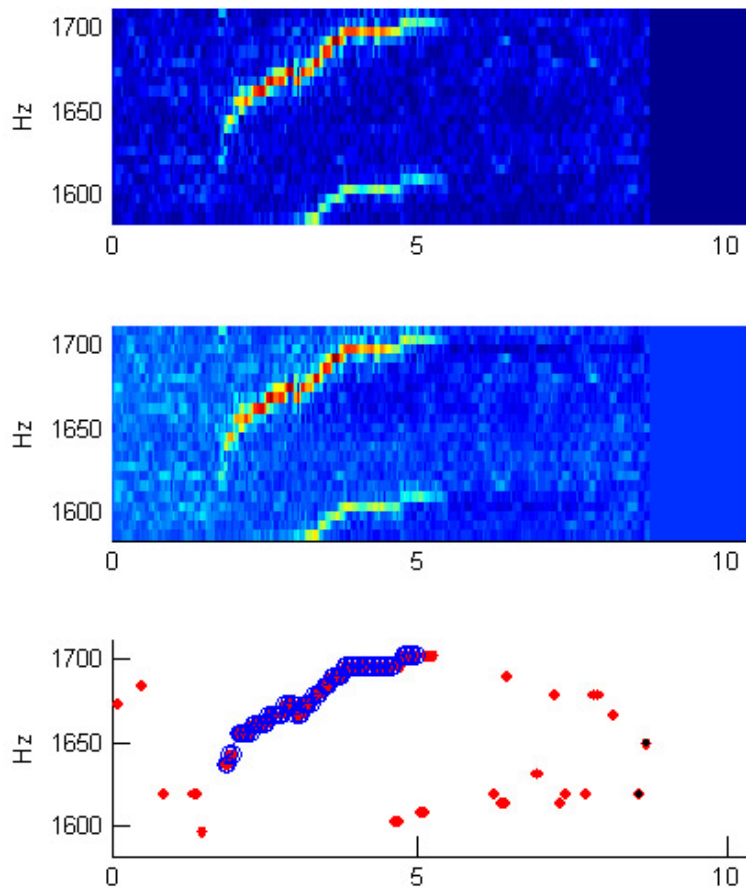
**Figure 2. Automated clustering of segments of spinner dolphin whistles that have been segmented and clustered using a modified version of Deecke and Janik's ARTWarp algorithm (Deecke and Janik 2006). Recognition of segment sequences within species is currently about 70% and needs to be improved before probabilistic sequence models will be useful in species classification.**

*DSC approach:* Figure 3 illustrates the spatial-temporal patterns of automatically detected and associated minke boing sounds with their DSC frequencies from 17 bottom mounted hydrophones at PMRF over the 30 minute period of the 5th International workshop localization data set. The workshop data only included hydrophones labeled B9, B8, B, B6, A9, A7, and A6 in the figure, the A1 to A9 phone labels represent a south to north string of phones to the west, while the B1 to B9 phone labels represent a similar south to north string of phones located to the east of the A phones. Each data point represents an automatic detection on the upper trace and the detections automatically determined DSC frequency on the lower trace. Automatic associations (assigning detections to a single sound) are indicated by color, the colors cycle between blue, green, red and black for different sounds. The plot indicates multiple animals each making multiple calls in this 30 minute period. Two suspected individuals sounds, at DSC frequencies of  $1383(\pm 5)$  Hz and  $1365(\pm 5)$  Hz, are apparent. At least 3 suspected individuals have DSC frequencies 1390 and 1415 Hz based upon the temporal arrival patterns.



***Figure 3. Automatic minke boing sound detections and DSC frequencies for 17 hydrophones at PMRF. Multiple individuals present making multiple calls over the 30 minute time span shown.***

Figure 4 provides spectrograms and outputs of a tonal detector for an Eastern Pacific minke sound (data courtesy of Shannon Rankin and Jay Barlow). The character of this signal is significantly different from minke boing sounds from the central Pacific, with a slowly varying frequency modulation component and very little constant-frequency content (see project proposal for a sample). The tonal detector (similar to that available in Ishmael) output is shown in the bottom trace as blue circles overlaid on the red spectral peaks which meet the tonal detection criteria (e.g. time and frequency separation of peaks).

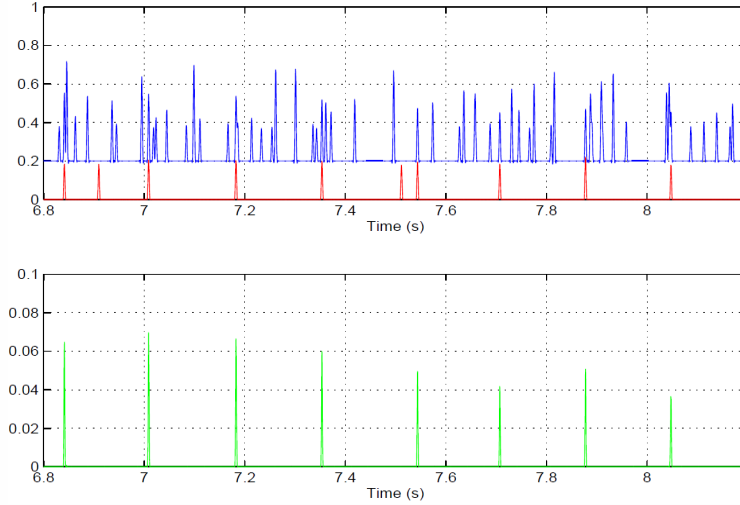


**Figure 4. Example of an eastern Pacific minke whale sound automatic tonal detection process for 10 s of data over a frequency band of 1580 Hz to 1720 Hz. (top) Raw spectrogram. (middle) Normalized spectrogram. (bottom) Red dots indicate peak detections while blue circles indicate a detected signal which meets the tonal criteria. Data provided courtesy of Shannon Ranking and Jay Barlow with NOAA/SWFSC.**

*CS-SVM approach:* This classifier was evaluated in-situ at the Southern California Offshore Range (SCORE) off San Clemente Is., CA and at the Atlantic Undersea Test and Evaluation Center (AUTC) off Andros I. in the Bahamas. The performance of the CS-SVM was compared to an alternate method which used simple frequency segmentation paired with post-detection filtering based on expected inter-click interval. The results show that the CS-SVM has significantly better precision than the frequency segmentation method, especially for beaked whales. While the CS-SVM rarely confuses beaked whales and dolphins, similarly to the frequency segmentation approach, the current CS-SVM feature set has limited ability to reliably distinguish between clicks from different dolphin species. Development and selection of feature sets to distinguish between dolphins while maintaining distinction of beaked whales is ongoing.

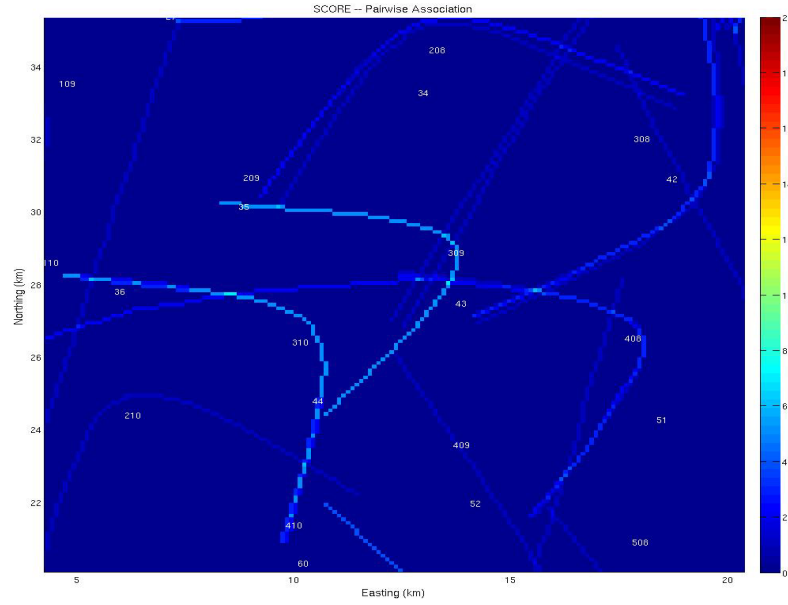
*Localization:* TDOA estimation is done using synthetic time series from two hydrophones. The synthetic series is produced from the times and amplitudes of detected clicks; the result is then smoothed and amplitude-compressed. Correlation was done in the frequency domain using the

smoothed and time-windowed synthetic time-series of one hydrophone and the ideal synthetic time-series of the other hydrophone. This produced a correlation result with no circular effects, and no overlap loss, provided time delays only in a restricted range were taken. See Fig. 5.

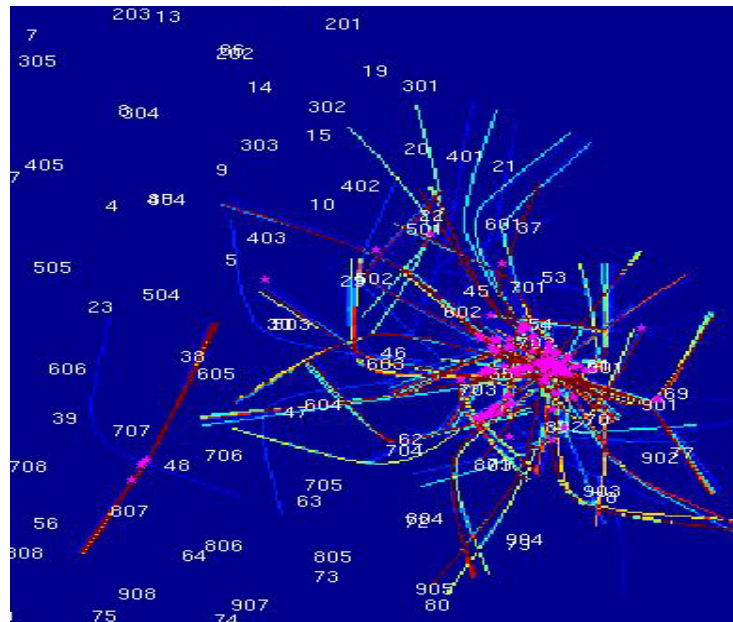


**Figure 5. (top) Example of hydrophone synthetic time-series for two hydrophones (blue and red curves) time-aligned by largest correlation peak. (bottom) Cross-multiplied synthetic time-series, effectively an estimate of the source time-series, showing a periodic pattern of beaked whale clicks.**

The second localization method being developed results in a 2-D histogram of TDOA information that can then be used to estimate the location of the vocal animals (Fig. 6). This method was found to be useful in the case of sparse detections but can become nearly impossible to interpret in the presence of high numbers of detections (Fig. 7). As such this method should be considered as a way to supplement multilateration in the event of detection on fewer than 3 sensors but should not be used instead of multilateration in cases where vocalizations are received on 3 or more phones.



**Figure 6.** *The intersections of hyperbolae defined by the TDOA of animal vocalizations as received by separate pairs of sensor can be used for localization.*



**Figure 7.** *When multiple animals and detection on numerous pairs of sensors is possible, determining unambiguous location from hyperbola crossing becomes quite difficult.*

## IMPACT/APPLICATIONS

For the Navy, passive acoustic monitoring (PAM) provides a means of long-term monitoring of many cetacean populations, especially over areas of high interest. Such areas are repeatedly subjected to Navy exercises involving intense sounds, especially multi-ship mid-frequency active (MFA) sonar. Currently, required environmental monitoring is dependent primarily on visual line transect surveys that are costly and, in the case of aerial surveys, significantly dangerous. In both the areas critical to the Navy and in other areas critical to marine mammals, PAM is dependent on automated DCL methods. The advanced DCL algorithms being developed here will make PAM more effective and efficient; the algorithm implementations across standardized interfaces that handle both real-time and pre-recorded data streams from diverse platforms will make them available to Navy fleet operators as well as the wider marine mammal research community.

## RELATED PROJECTS

“Passive Acoustic Monitoring for the Detection and Identification of Marine Mammals” (N00014-08-1-1199) award to PI Roch in 2008-10. This effort helped produce the *Silbido* detector that will be the basis for the research here in tonal sound detection and classification.

“Passive Autonomous Acoustic Monitoring of Marine Mammals with Seaglidors” (N00014-10-1-0387) award to Mellinger (and Klinck). The methods developed here are likely to be implemented in the Seaglider acoustic system for real-time detection and classification of marine mammal sounds.

“Acoustic Metadata Management and Transparent Access to Networked Oceanographic Data Sets” (NOPP N00014-11-1-0697) award to PI Marie Roch, Co-PI Simone Baumann-Pickering, John A. Hildebrand, et al. A metadata management system is being developed, which allows access to locally stored acoustic detections and metadata and links in a standardized way to external sources, such as oceanographic or ephemeris data. We will design our DCL plugins to provide outputs that can easily be stored in the acoustic metadata database.

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- Jarvis, S.M., R.P. Morrissey, D.J. Moretti, J.A. Shaffer and N.A. DiMarzio. In review. Detection, localization and monitoring of marine mammals in open ocean environments using widely spaced bottom mounted hydrophones. Submitted to *J. Acoust. Soc. Am.*

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